How to Make a Neutrino Beam

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NOvA Summer Seminar Series

Outline

- Basics of neutrino production
  - Focus on areas relevant to Fermilab
- Walkthrough of NuMI – a representative, modern neutrino beam
- Challenges for neutrino beams
  - Intensity and Precision
- Alternative techniques

The First Neutrino "Beam"

- In 1957, Brookhaven AGS and CERN PS first accelerators intense enough to make ν beam

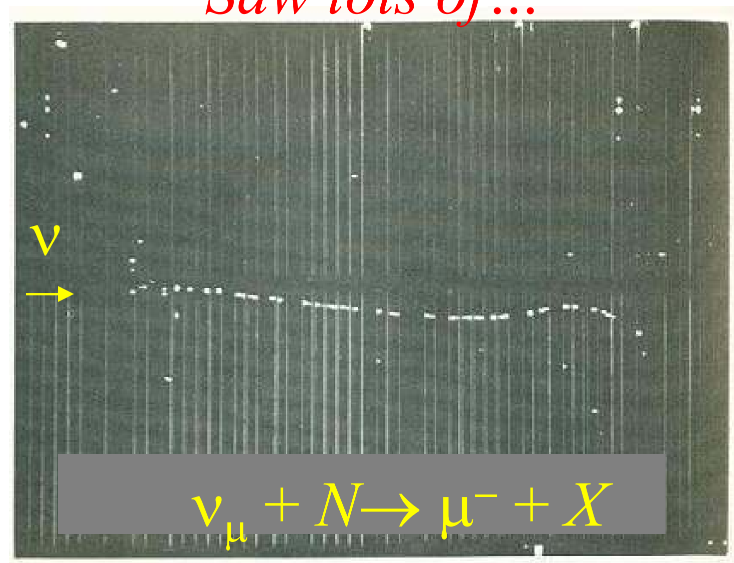
$$p + Be \rightarrow \pi^+ + X, \qquad \pi^+ \rightarrow \mu^+ \nu$$

- 1962: Lederman, Steinberger, Swartz propose experiment to see

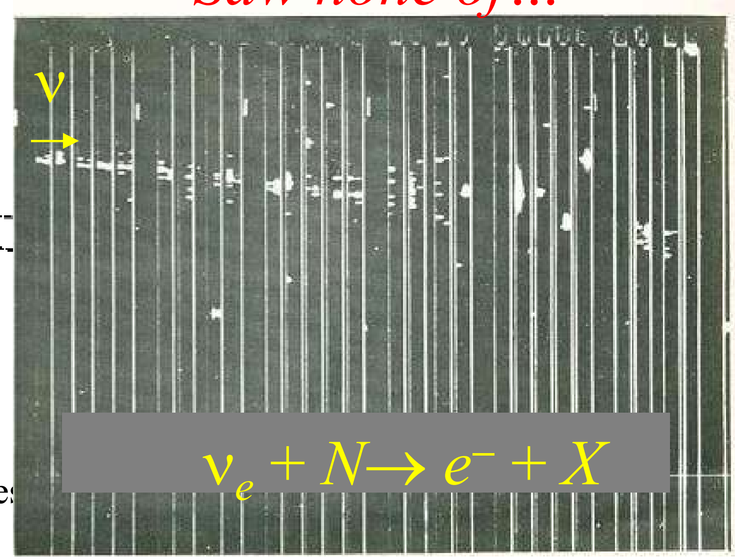
$$\nu_\mu + N \rightarrow \mu^- + X$$

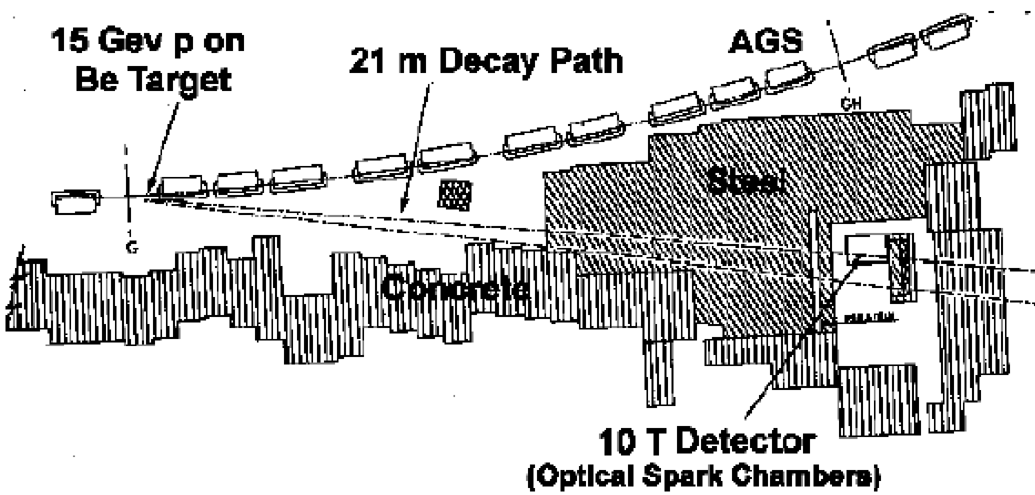
(Phys.Rev.Lett. ***9****, 36 (1962))*

Saw lots of…



Saw none of…



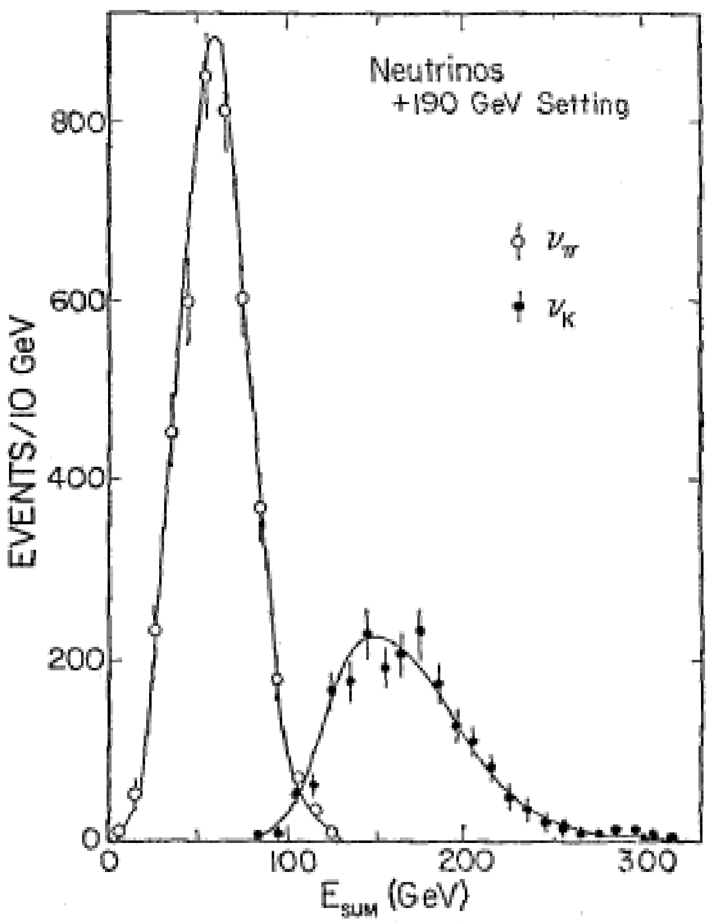


Why a Beam?

- Natural sources exist – but they are very weak and not necessarily well understood
  - Solar and atmospheric neutrinos only understood once oscillations were established and well understood
    - Moving from observation to experiment
  - Supernovae are hard to come by
- Artificial beams are controlled and intense
  - We decide when, where, and how the beam is generated
  - Detectors are placed strategically
  - I'll concentrate on beams, but reactors and other non-beam artificial sources contribute similarly
- Applications:
  - Today neutrino oscillation is the first focus
  - Probe of nuclear structure
  - Observation of the neutral current
  - Demonstration of neutrino flavor (muon, tau)
  - Measurement of weak mixing angle

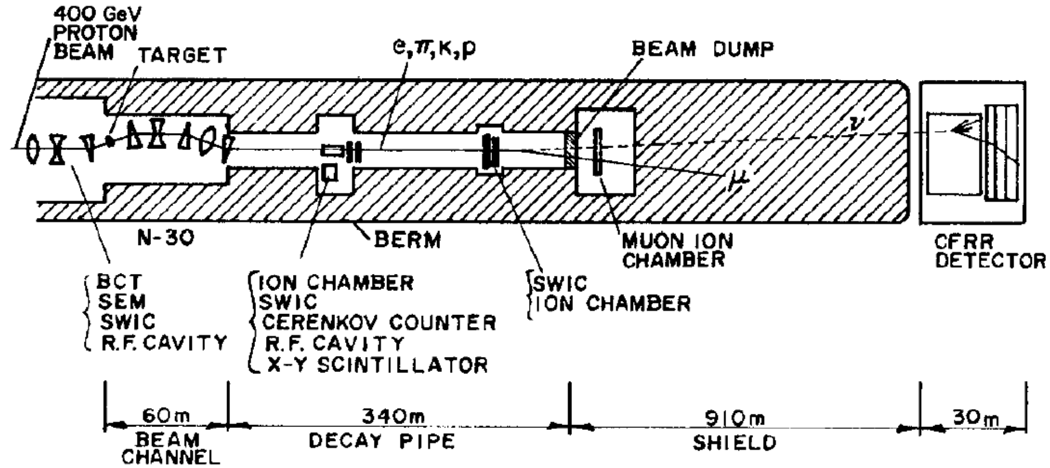
Dichromatic NBB

- Modern neutrino beam previous to oscillation searches



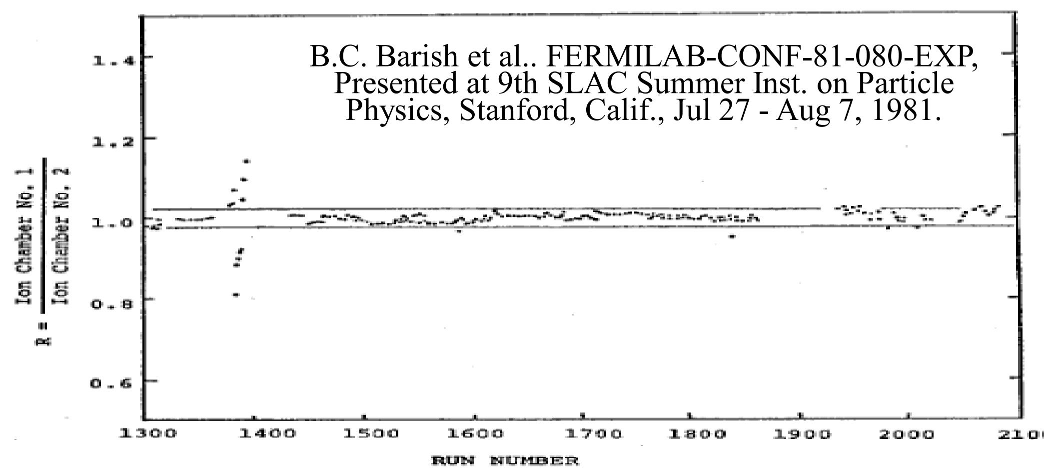
•B.C. Barish et al.. FERMILAB-CONF-78-046-EXP, Presented at 3rd Int. Conf. on New Results in High Energy Physics, Nashville, Tenn., Mar 6-8, 1978

•P. Limon et al, FNAL-Pub-73/66



- Channel accepts $\Delta p/p \sim$ 5-10%

$$E_\nu \approx \frac{(1-\frac{m_\mu^2}{m_{\pi,K}^2})E_{\pi,K}}{1+\gamma^2\theta^2}$$



B.C. Barish et al.. FERMILAB-CONF-81-080-EXP, Presented at 9th SLAC Summer Inst. on Particle Physics, Stanford, Calif., Jul 27 - Aug 7, 1981.

Sources of Neutrinos

- Weak Decays
  - Elements, pions, muons…
- Choose energy scale to make muons, tau
  - Charged current interaction best way to measure flavor
- Pion decay is optimal
  - Simple, two body, pure muon-neutrino source
- Kaon & Muon decay often come along for the ride
  - Produce backgrounds of electron-neutrinos
  - More complicated decay channels and kinematics
  - Depends on history (polarization)
- Tau neutrinos production require much heavier parents
  - Charm is the best source

Pion Decay

- Neutrinos produced at random direction in pion rest frame
  - Booster in the direction of the beam
  - Ultimate energy determined by the decay angle with respect to the boost, in the lab:

$$E_\nu \approx E_\pi \frac{1-m_\mu^2/m_\pi^2}{1+\gamma^2\theta^2} \approx \frac{0.43E_\pi}{1+\gamma^2\theta^2}$$

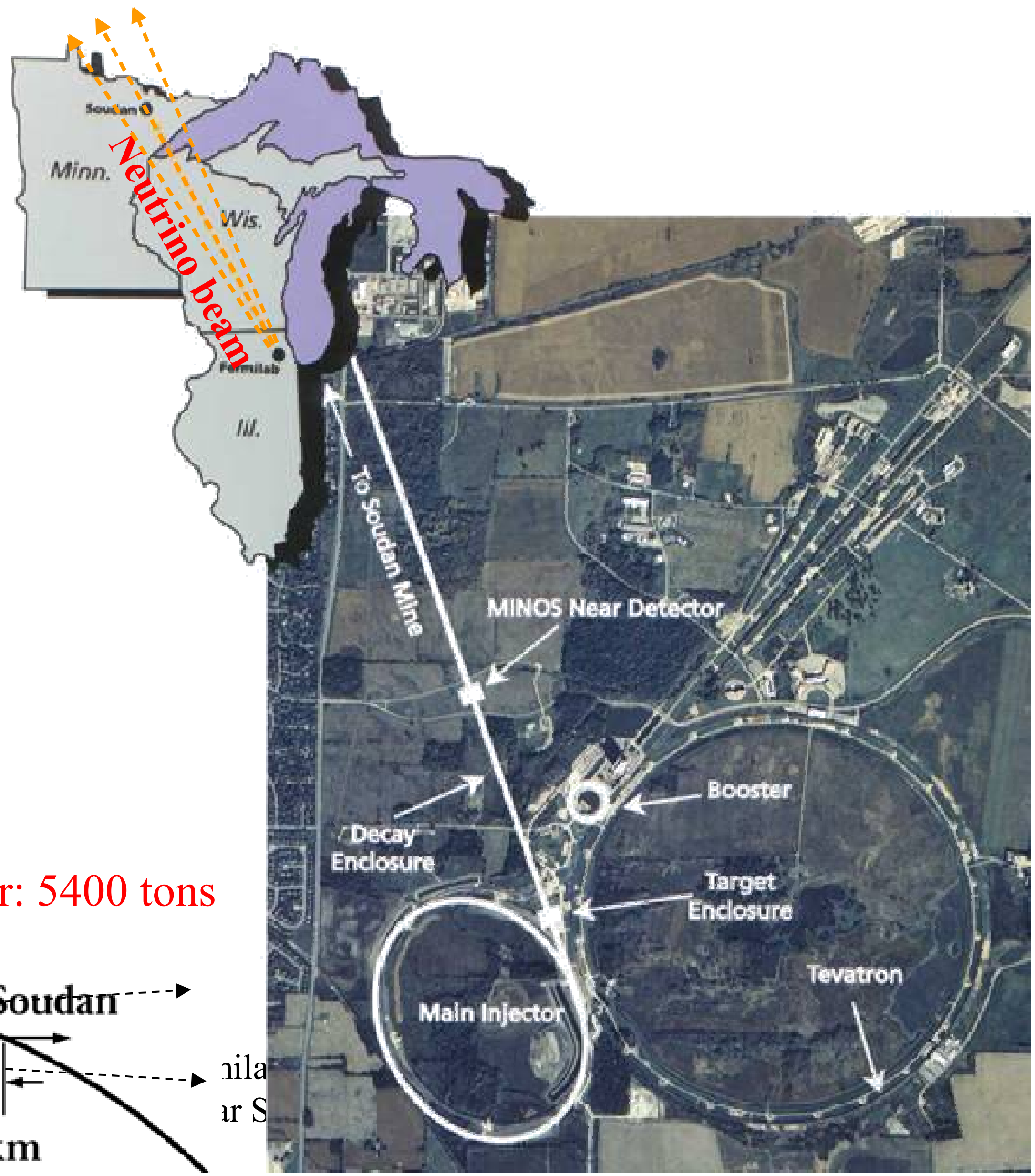
  - Muon carries the balance of the energy
- Flux is also affected such that the beam is strongly directed in the direction of the pion velocity:

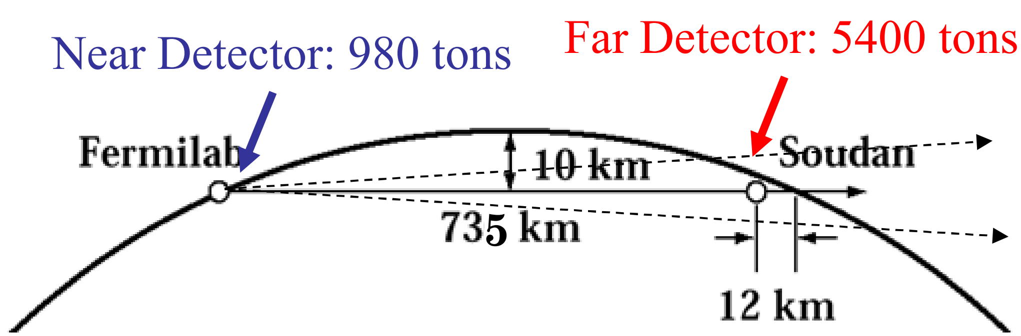
$$\frac{dN}{d\Omega} \approx \frac{1}{4\pi}\left(\frac{2\gamma}{1+\gamma^2\theta^2}\right)^2$$

- All two-body decays have this functional form. Three body-decays are boosted in the same way, but are complicated by the decay kinematics

The NuMI Facility

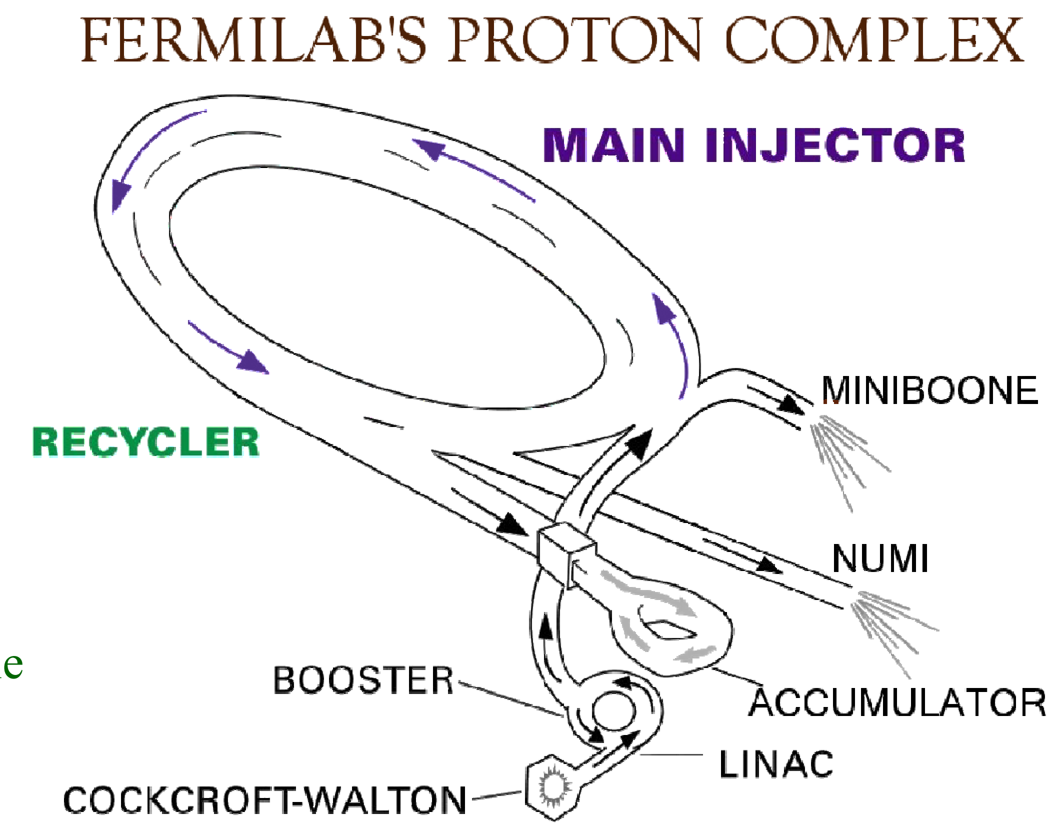
- High-power neutrino beam for oscillation experiments
  - ➢ Beam tilted 3.3° down into the earth
- Neutrino beam travels to northern Minnesota
  - ➢ 735 km baseline
  - ➢ Intense source at Fermilab
  - ➢ Oscillated source in Minnesota
- Commissioned in 2004
- Operating since 2005





Protons as Raw Material

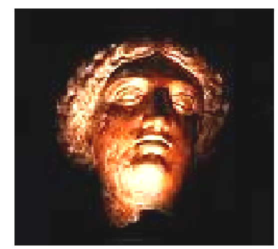
- 120 GeV protons from the Main Injector
  - NuMI Designed for as many as 4×10^{13} protons/pulse
    - 10 μs pulse every 1.9 s
    - 400 kW design power
- Shared proton capability
  - Antiproton Source (collider)
  - MiniBooNE beam
- Being upgraded for NOvA
  - Use of the Recycler to reduce cycle time
  - 700 kW: as much as 5×10^{13} protons/pulse every 1.333 s



Users

- MINOS – Main Injector Neutrino Oscillation Search
  - Initial user – built concurrently with NuMI
  - Muon-neutrino disappearance search

- MINERvA experiment in operation
  - Sited in MINOS Fermilab hall
  - Extensive portfolio of high-statistics measurements



- NOvA experiment in construction
  - New far detector in northern Minnesota
  - New near detector in new underground hall
  - Electron-neutrino appearance search

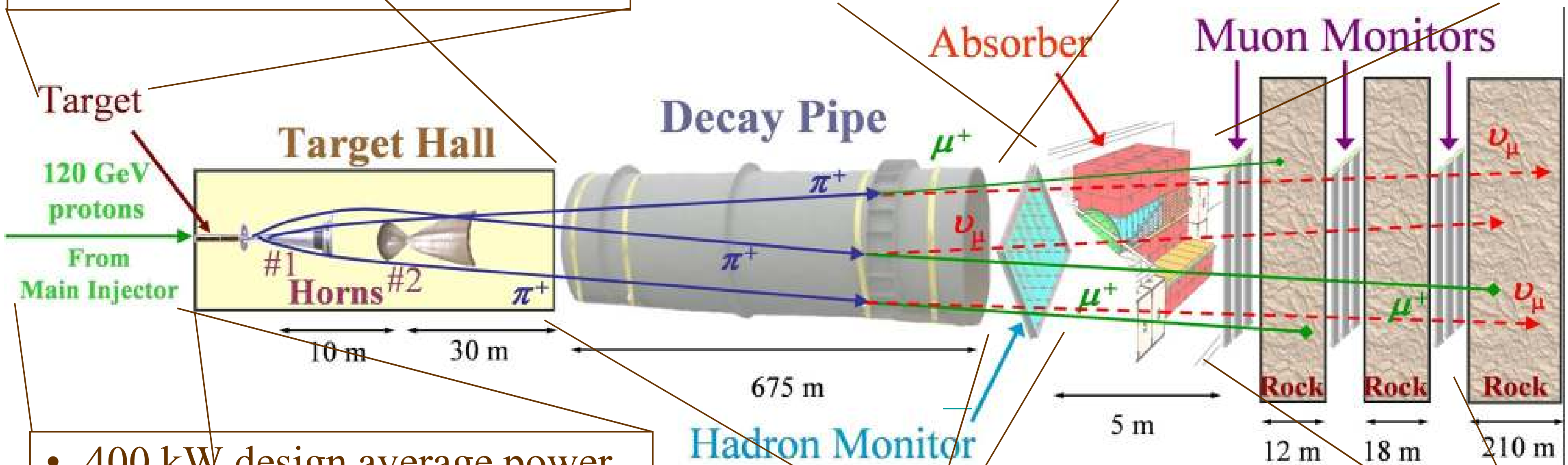
The NuMI Beam

"Neutrinos at the Main Injector"

- 2 interaction length, C target
- Produces π^+, K^+ mesons

- 2 m diameter
- Roughly decay length for 10 GeV π^+
- He-filled

- Absorbs ~ 40 % of beam power
- Allows high-energy muons to penetrate



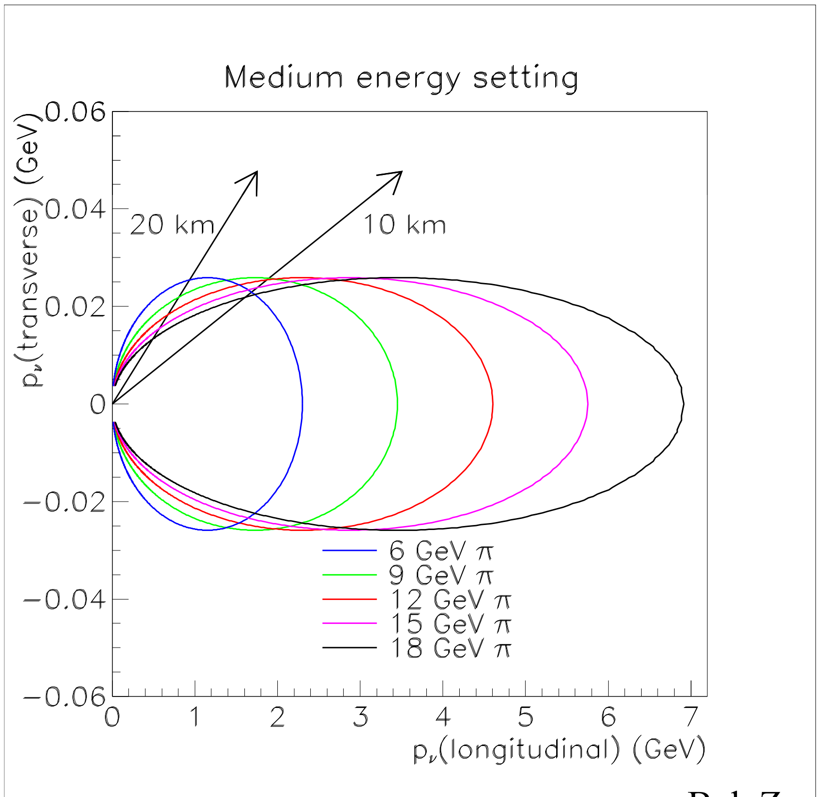
- 400 kW design average power
- 700 kW upgrade for NOvA
- $\sigma \sim 1$ mm

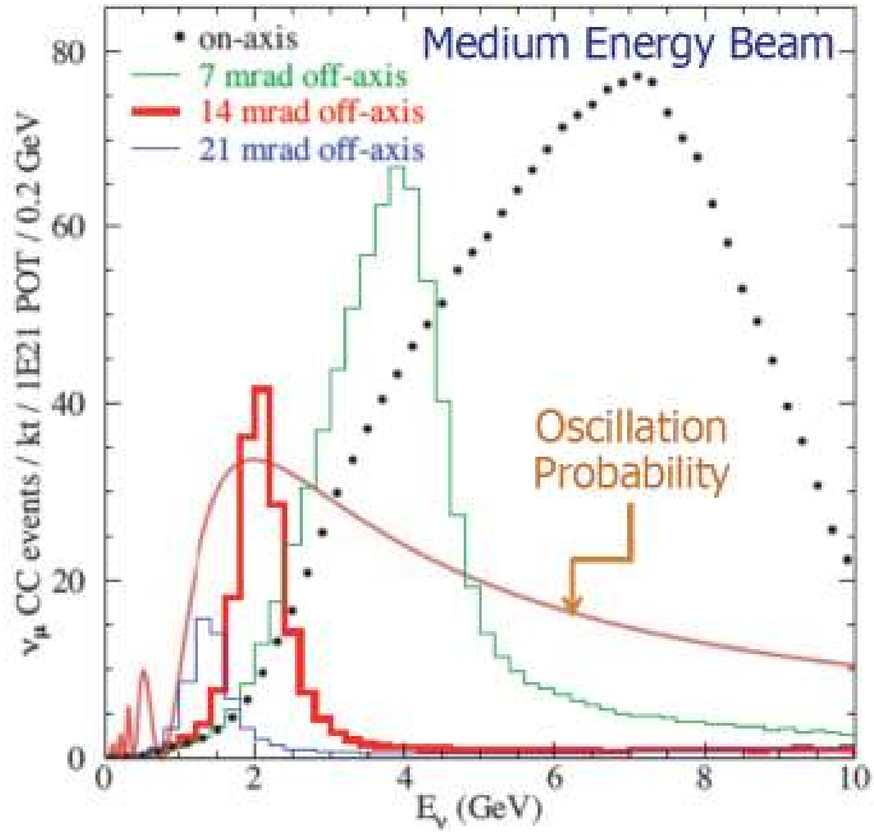
- Pulsed focusing horns
- Toroidal magnetic field
- Parabolic inner conductor profile
- Focuses meson momentum band

- Measure hadron & muon fluxes
- Arrays measure distributions

Off-Axis Beam

- Technique used by T2K, NOvA (first proposed by BNL)
  - Fewer total number of neutrino events
  - More at one narrow region of energy
  - For ν_μ to ν_e oscillation searches, backgrounds spread over broad energies





Challenges to Conventional Neutrino Beams

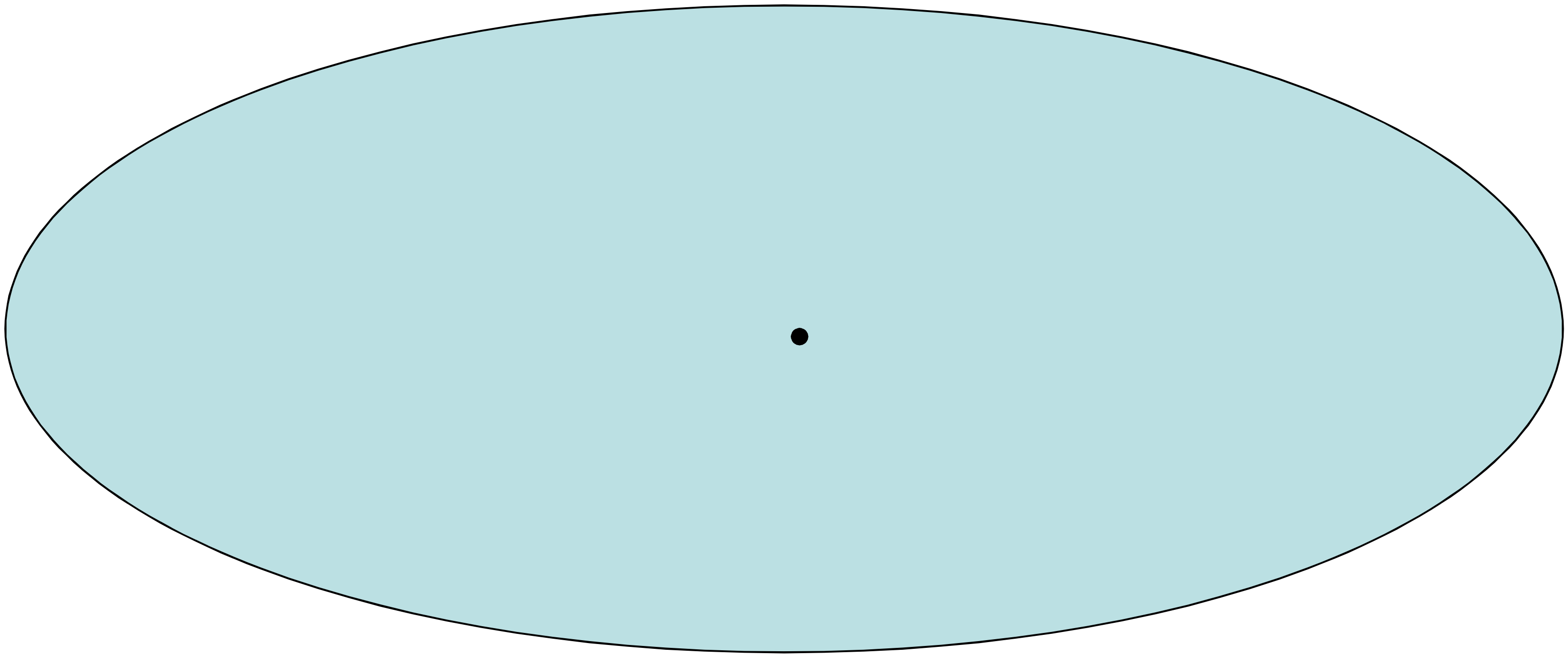
- Proton beams
- Targets
- Horns / focusing
- Precision
- Instrumentation
- Hadroproduction Modeling & Experiments
- Radiation Protection
- Radionuclide handling

Challenge: Proton Beam

- Increased beam power translates directly into neutrinos
- However, there are limitations on the beam delivered:
  - Spot size: small enough to optimize focusing, large enough to preserve target
  - Pulse length: short enough to allow short horn current pulses, long enough to preserve target
  - Stability: errant pulses can distort neutrino spectrum and destroy equipment
  - Losses must be kept very low in transfer lines, or more extensive shielding is required
- Single-turn extraction with tight beam optics is usually optimal
  - Larger emittances must be compensated by stronger focusing

Challenge: Proton Beam

- SNS & NuMI proton beams to scale:



- 200 mm x 70 mm vs. 1.1 mm x 1.1 mm
  - ➢ SNS target experience is not directly transferrable

Challenge: Targets

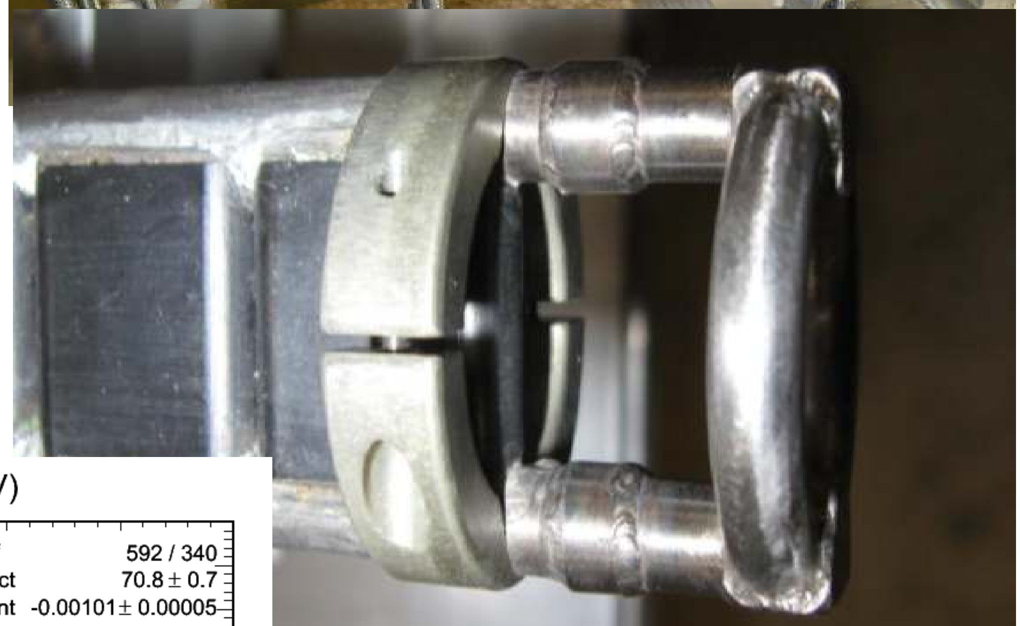
- Optimal target:
  - Low-Z to optimize pion production (minimize energy deposition in target & horn)
  - High density to stay within the Horns' depth of focus
  - Roughly two nuclear interaction lengths long
  - The optimized width to allow a certain amount of reinteraction, but limit absorption
- But, the target must survive for a non-negligible duration
  - Material must withstand thermomechanical shock
  - Material must withstand radiation damage
  - Heat must be removed
  - Supporting materials (e.g. water & pipes) must be far enough from the beam to avoid boiling
- Above contradictions drive us to graphite & beryllium
  - Water cooling is the baseline, but air is not out of the question
  - **R&D** has a substantial capability to improve the efficiency of neutrino production

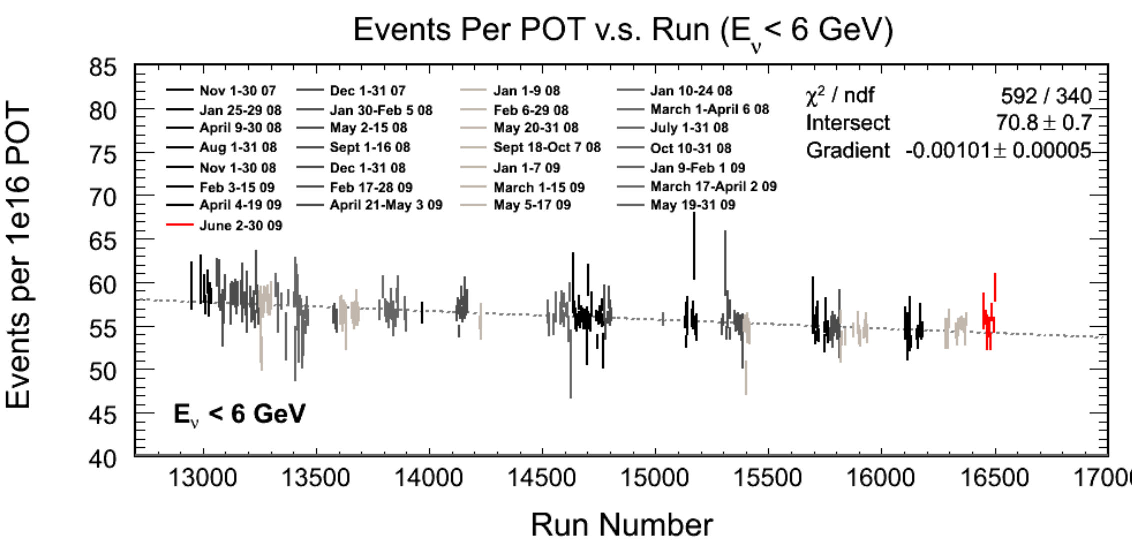
Experience with MINOS targets

	Max. Proton/pulse	Max. Beam Power	Integrated Protons on Target
Target Design specification	4.0e13 p.p.p. at 120 GeV	400 kW	3.7 e20 p.o.t. or 1yr minimum lifetime
NT-01	3.0 e13	270 kW	1.6 e20
NT-02	4.0 e13	340 kW	6.1 e20
NT-03	4.4 e13	375 kW	3.1 e20
NT-04	4.3 e13	375 kW	0.2 e20
NT-05	4.0 e13	337 kW	1.3 e20
NT-06	3.5 e13	305 kW	0.2 e20
NT-01 rerun	2.6 e13	228 kW	0.2 e20
NT-02 rerun	3.8 e13	330 kW	0.4 e20
NT-07	4.0 e13	345 kW	2.5e20

Target Issues

- Predominant failure mode was cooling
  - Also an issue for horns
  - Many lessons were learned in design and in quality control
- NOvA target is more robust in its design
  - Made possible by being outside of the horn.
- Graphite degradation was observed on one target
  - May ultimately limit the performance of the material





MINOS / NOVA / LBNE Targets

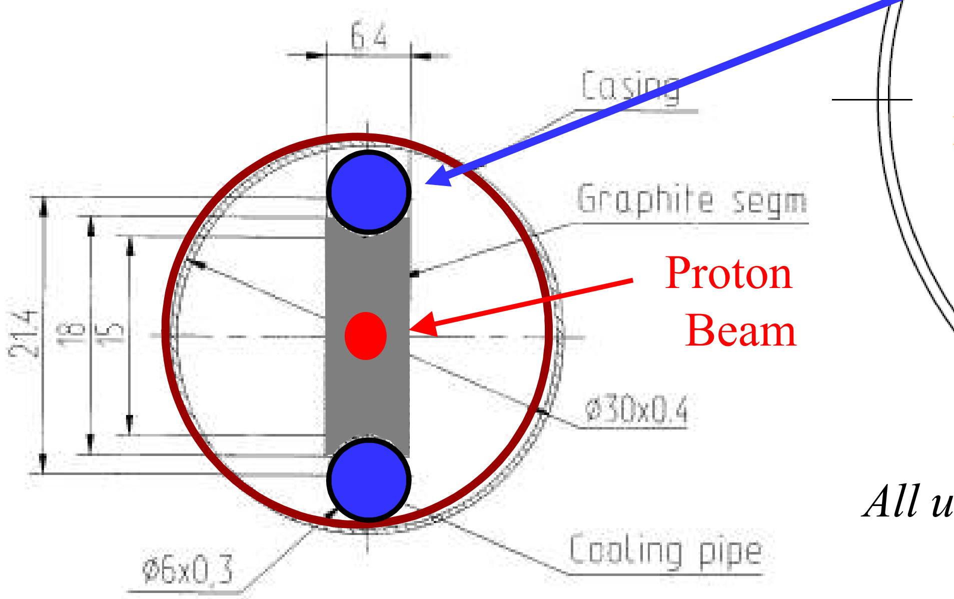
	NUMI / MINOS	NUMI / NOVA	LBNE
Distance to far detector	735 km	810 km	1300 km
Desired n energy	1 to 15 GeV	2 GeV	0.8 & 2.7 GeV
Detector Off-beam-axis angle	0	14 mrad	0
Design beam power	400 kW	700 kW	700 kW initial
Energy per proton	120 GeV	120 GeV	120 GeV
Number of horns	2	2	2
Target length	0.95 m	1.2 m	1 m
Distance between target downstream end and horn	1.6 m to -0.6 m (Variable)	0.2 m (Not in horn)	-0.95 m (In horn)
Protons/spill	4.4 E13 max.	4.9 E13	4.9 E13
Repetition rate	2.2 sec	1.33 sec	1.33 sec

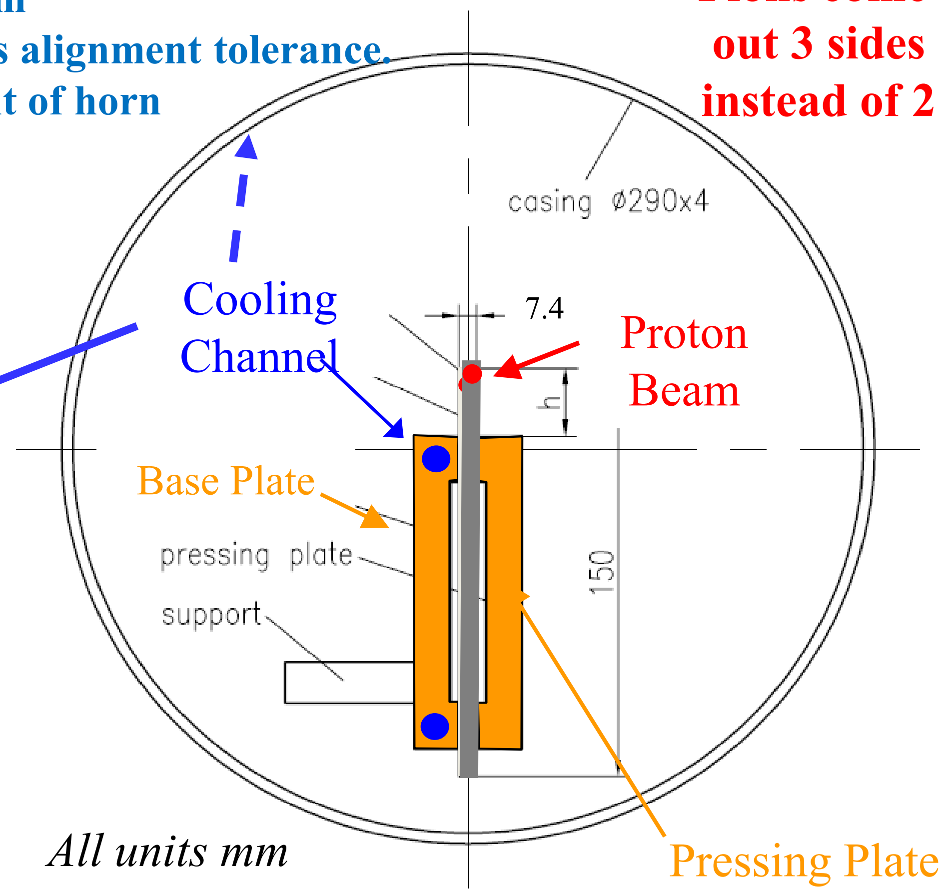
MINOS & NOvA Target Comparisons

MINOS beam spot size of 1.1 mm RMS is increasing to 1.3 mm for NOVA, increasing 6.4 mm target width to ~ 7.4 mm
- reduces the neutrino flux ~ 1%, but eases alignment tolerance.
NOvA target cooling simplified by being out of horn

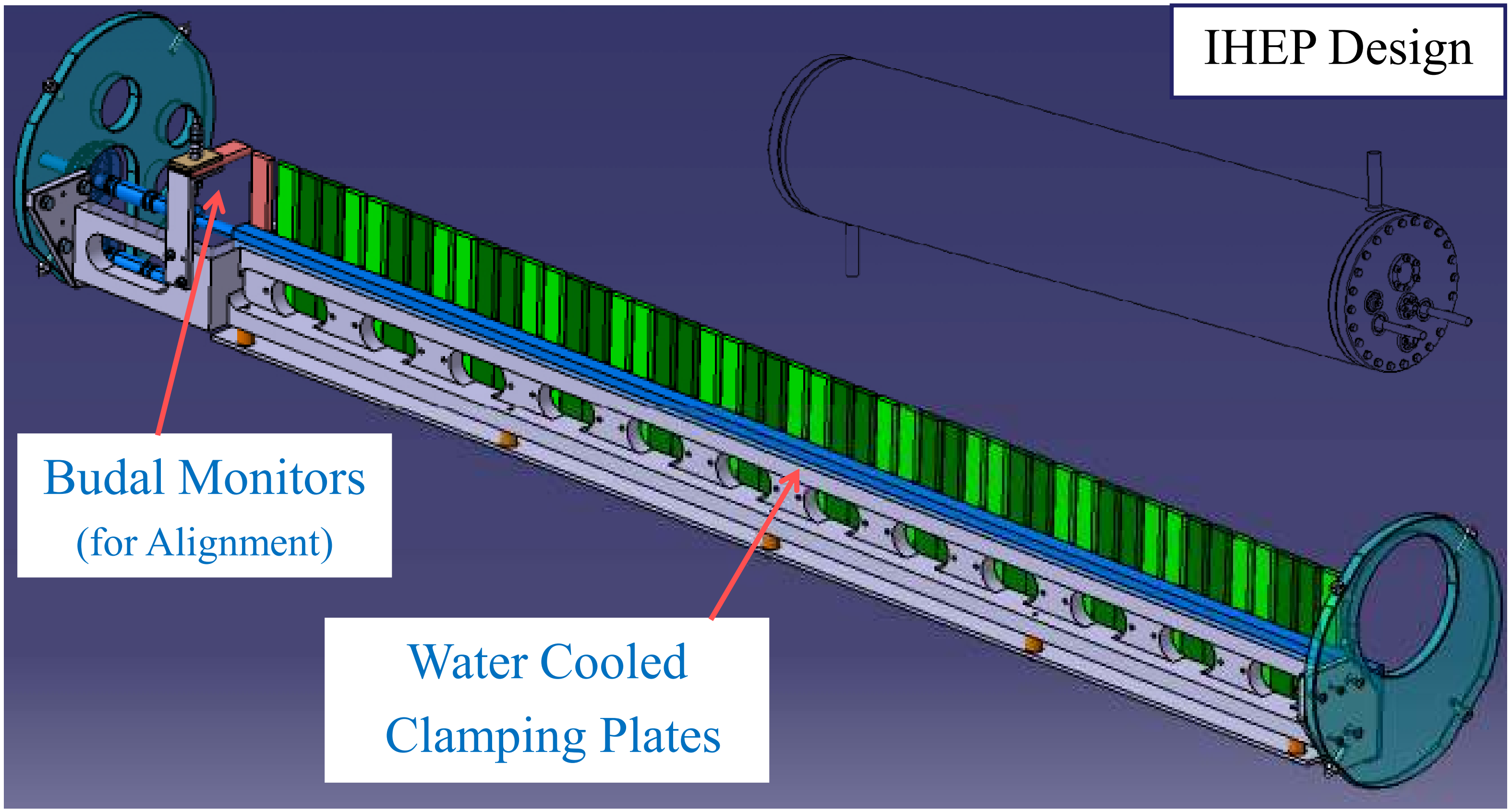
Pions come out 3 sides instead of 2

Spacing between fins
0.5 mm / 24 mm versus 0.2 mm / 20 mm





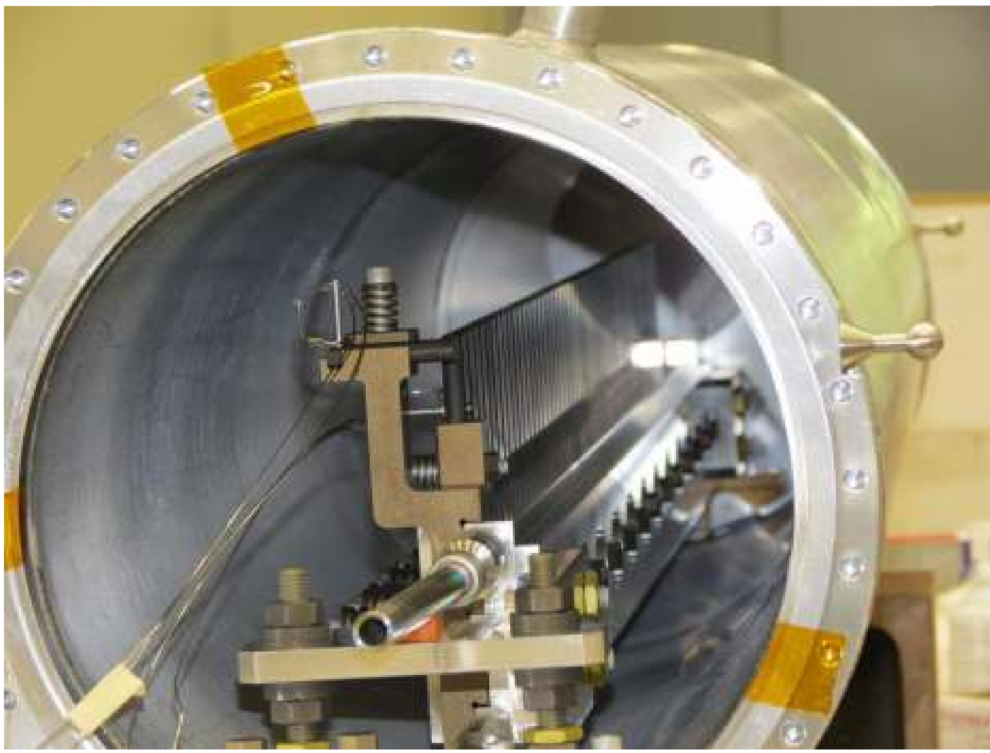
NOVA Target



Nominal max. beam power 700 kW

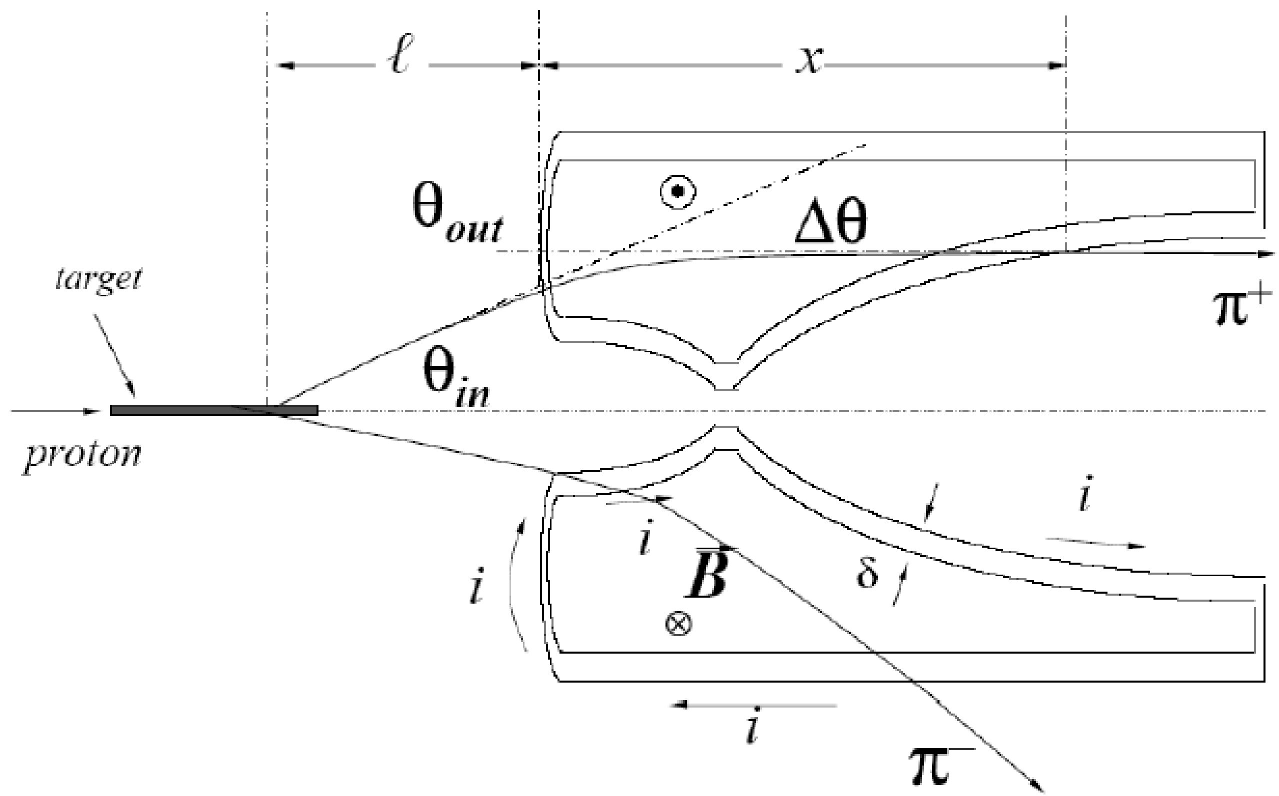
NOvA Target Production

- Proceeding with two construction paths:
  - 1st target built @ RAL
  - One each under construction at RAL & Fermilab
- Hope to have a target lifetime of ~ 1 year



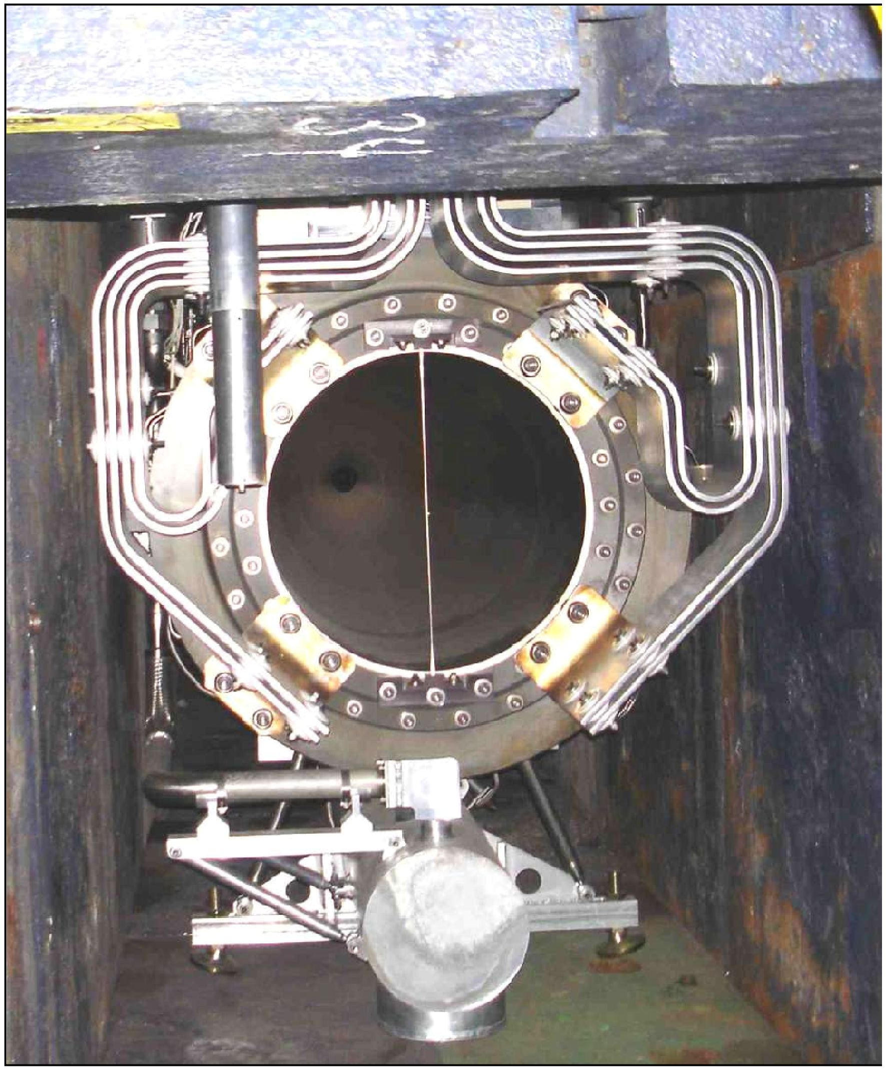
Horn focusing

- Current sheet flows along large inner and outer conductors to forma toroidal magnetic field
  - ➢ Focuses in both planes
  - ➢ Particles pass through the conductor material



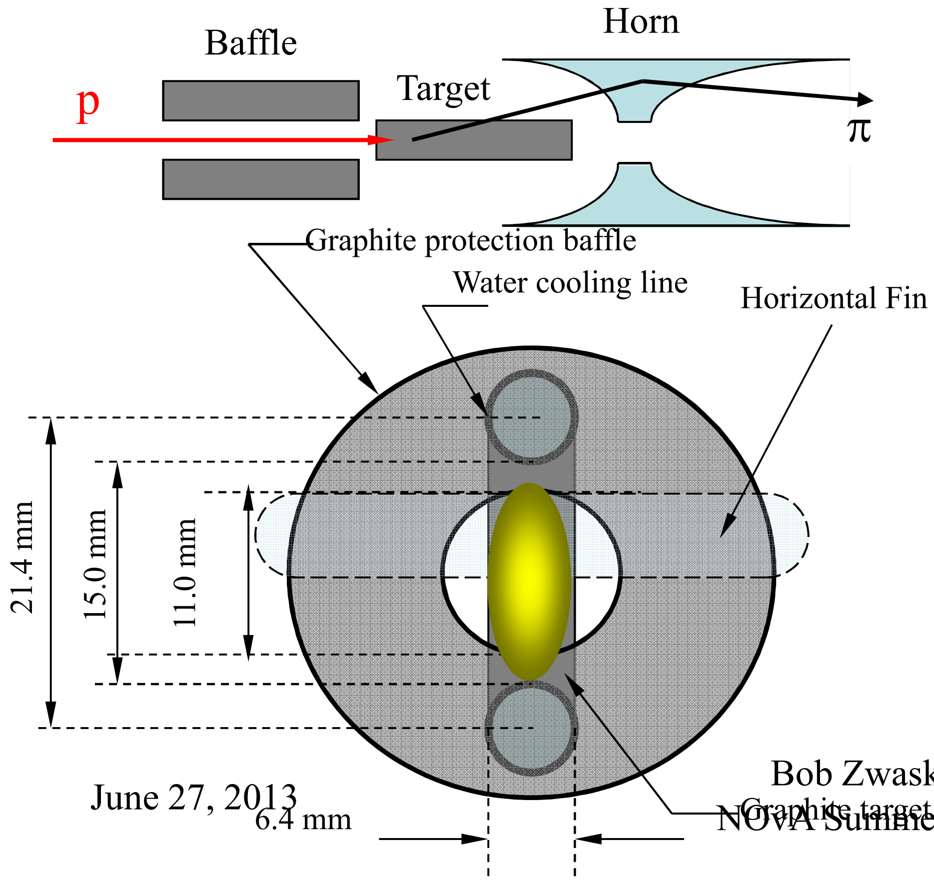
Challenge: Horn Focusing

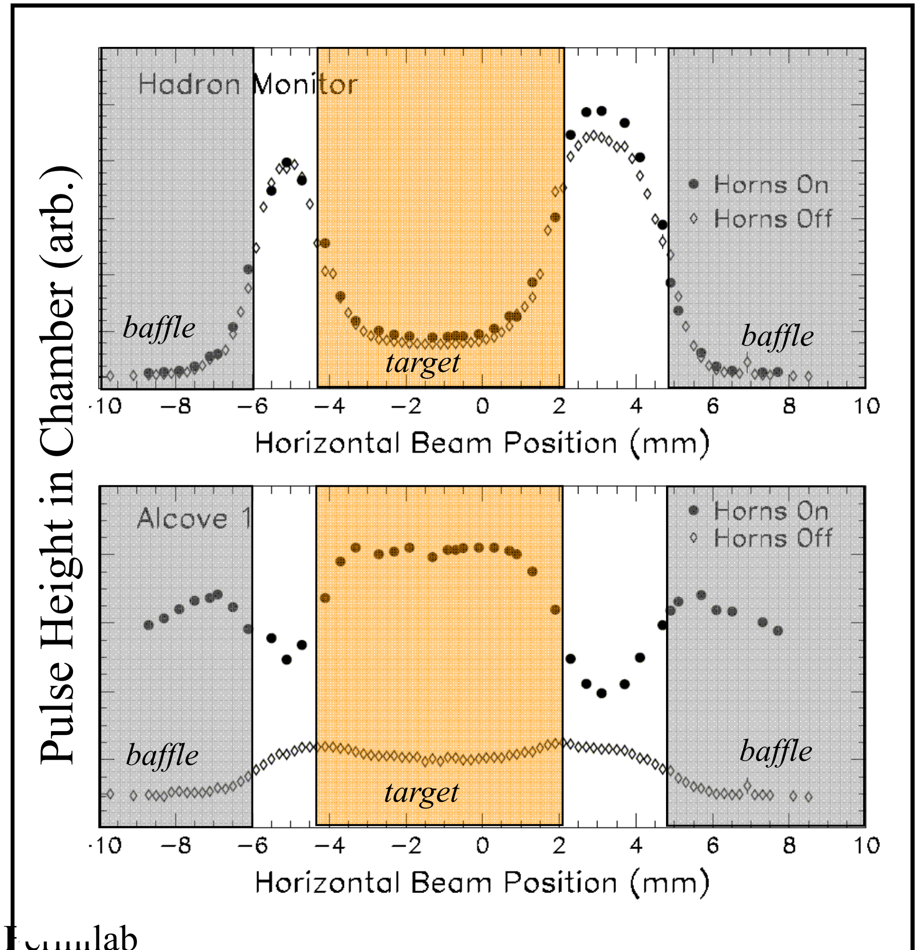
- Horns have a limited depth of focus
  - For a particular momentum in NuMI, roughly:
    - ± 5 mm transversely
    - ± 15 cm longitudinally
  - Target is much longer in *z* !
    - Not so bad: want a broad energy spectrum
  - Horn shapes and schemes can be optimized, even augmented by alternative focusing methods
- Horn currents are limited by ohmic and beam heating (~ 200 kA)
  - Higher currents would allow more efficient focusing
- Horn materials cause absorption and heating
  - Presently aluminum
  - **Beryllium is an R&D option**



Challenge: Precision NuMI Target Alignment

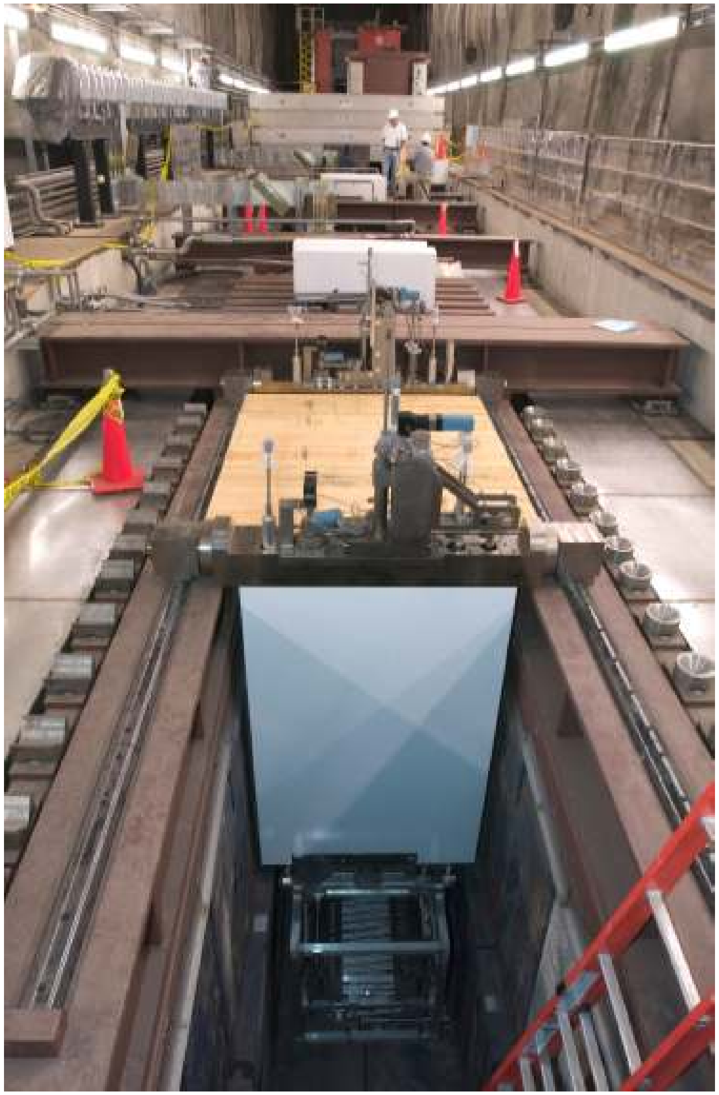
- Proton beam scanned horizontally across target and protection baffle
- Hadron Monitor used to find the edges
  - Measured small (~1.2 mm) offset of target relative to primary beam instrumentation.
  - Systematic effect of this misalignment would exceed statistical uncertainties





Why was the Target Misaligned?

- Aimed at the target by using correctors and 2 BPMs, 10 & 20 m upstream
  - BPM precision better than 0.1 mm
  - Everything aligned optically to few tenths of a mm
- Loading of the target hall
  - Shielding piled on top after the optical survey – this can be corrected
- Thermal deviation
  - Stations are fixed at different locations, move relative to eachother as temperatures change
  - Much more difficult to reduce



These Issues are Everywhere

- Gate at the top of my stairs installed in summer

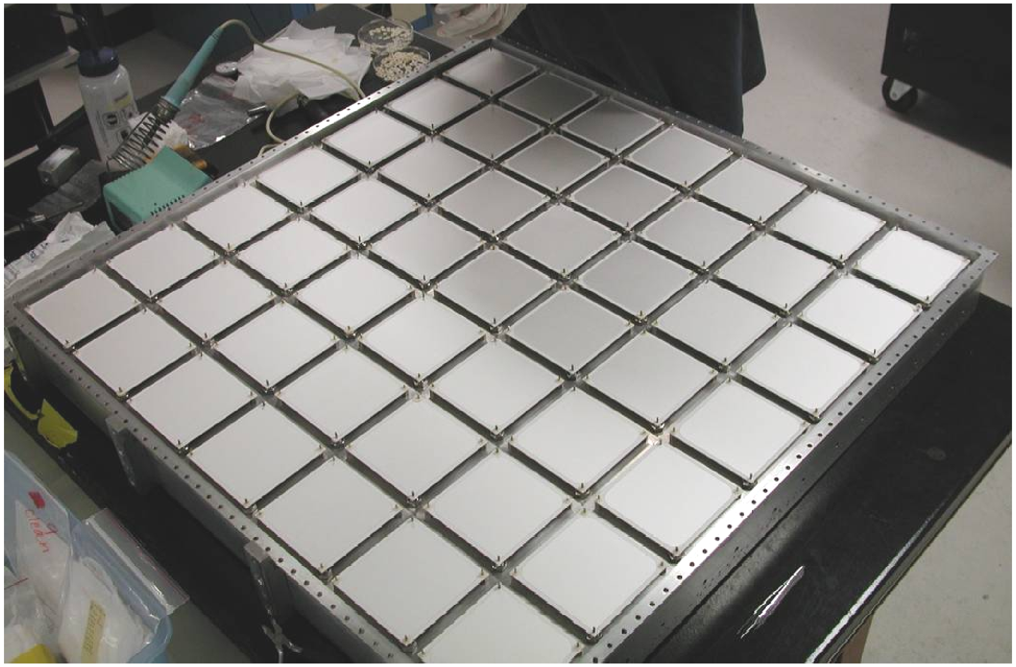
Tight Closure

Misaligned by ~ 2 mm

- Change of seasons in a temperature-controlled building caused a misalignment of 2 mm
  - ➢ Will not close in winter!
- This difference accumulated over only 1 m of span
  - ➢ Here, it is a safety issue!
- We are fortunate we only had ~ 1 mm to deal with in NuMI

Challenge: Instrumentation

- Instrumentation can be used to measure beamline variations and to reduce the experimental limitations from them
- This instrumentation often needs to live within the secondary beam
    - Radiation-hard
    - Large signals
    - Cooling
- **R&D** on instrumentation would improve the precision of neutrino experiments



A Note on Near Detectors

- Differential Neutrino Event Spectrum:

$$n(E_R) = \int dE_T \phi(E_T) \sigma(E_T) \varepsilon(E_R; E_T)$$

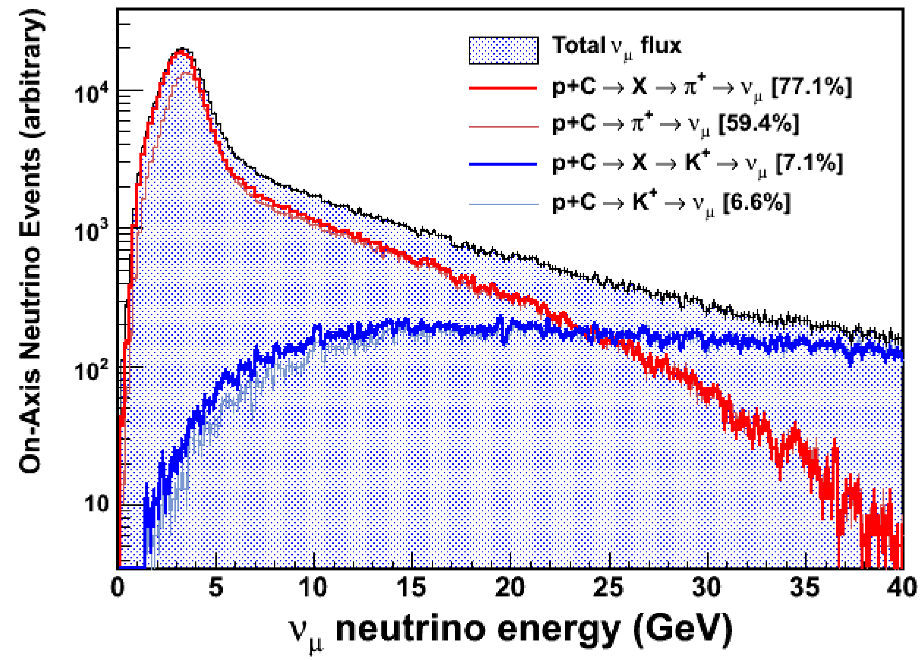
  - ➢ Depends on flux, cross section, and efficiency
    - Each has uncertainty
- A near detector reduces the uncertainty
  - ➢ Measures event spectrum at near location
    - Unfolding the cross sections and efficiencies gives the flux at near location
    - MC gives flux differences between detector locations
      - Less uncertain than absolute flux
    - Refold with far cross sections and efficiencies
  - ➢ Works best if detectors are the same
- For fashionable detector technologies (water, argon) the near detector must be substantially different than the far
- **Conclusion:** a near detector helps, but is not a panacea
  - ➢ Flux modeling crucial
  - ➢ Better cross section & efficiency knowledge helps

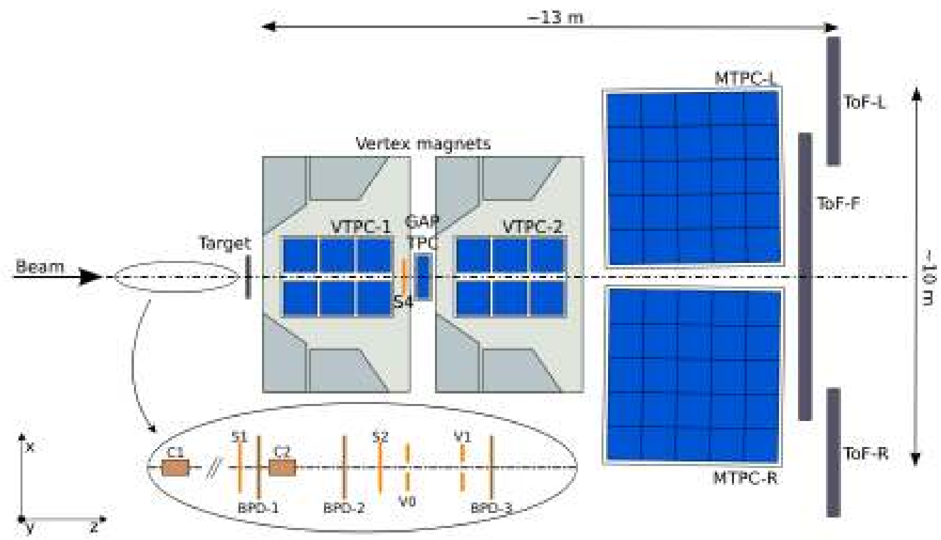
Challenge: Beam Modeling

- Modeling by hand from measured production cross sections falls well short in the required accuracy
- MC hadroproduction codes are used:
  - **GEANT:** gold standard, open code, but hadroproduction is tuned more for showers
  - **FLUKA:** best data agreement with neutrino experiments, but closed code – trust is not universal
  - **MARS:** well-used at Fermilab and good data agreement, but not a fully-available code and parts are closed
- GEANT is the most trusted code, but least accurate
- **Effort is needed** to tune codes and make them more useful
  - This does limit neutrino experiments

Challenge: Hadroproduction

- Simulations give a spectrum
  - But, what is the uncertainty?
- Hadroproduction experiments can constrain simulations, or directly give input to experiments' flux estimation
- Presently, NA-61 at CERN is exploring hadroproduction
  - Gradual series of measurements – not an exhaustive program
  - Some detector limitations mean that some important distinctions in parameter space can't be made
- **Solution:** a dedicated, exhaustive program of hadroproduction measurements could dramatically improve neutrino beam simulation



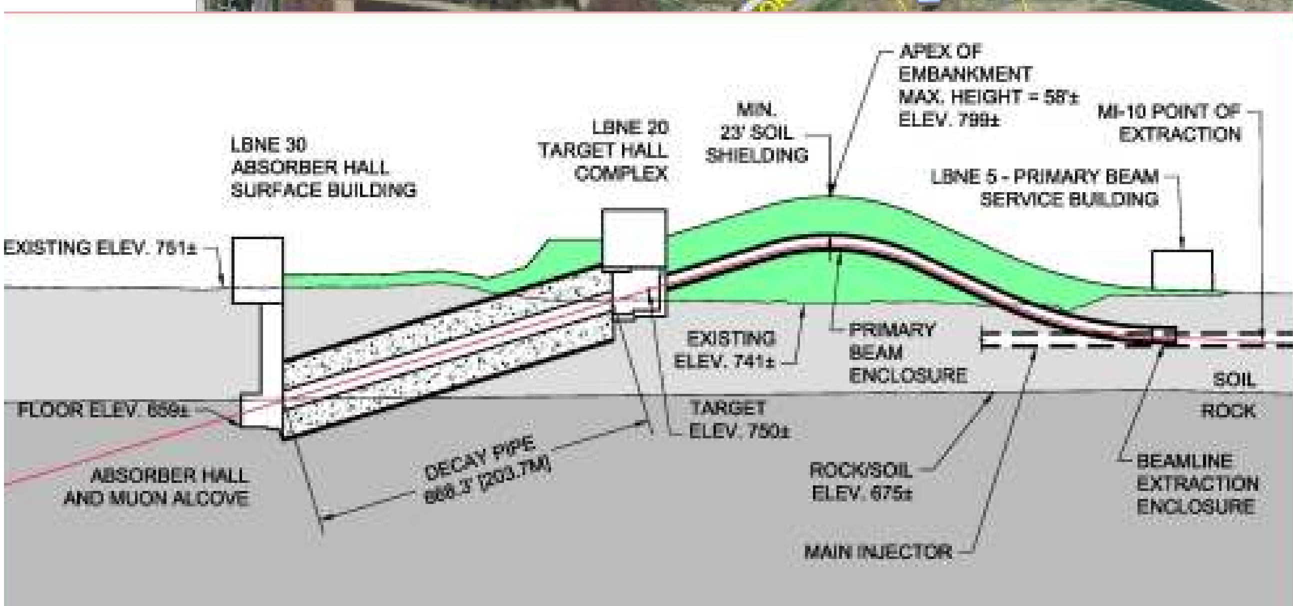


Challenge: Radiation/Radionuclide Management

- Shielding is not exciting
- But, it can drive the cost
- LBNE design has an ocean of concrete, an expensive hydro-control system, and a closed air-cooling system
- Substantial cost-savings could be realized if more efficient shielding or management systems could be proven to be adequate
- Issues:
    - Penetration of radiation
    - Migration of radionuclides
    - Radiation-induced corrosion

The Future

LBNE Beamline Reference Design

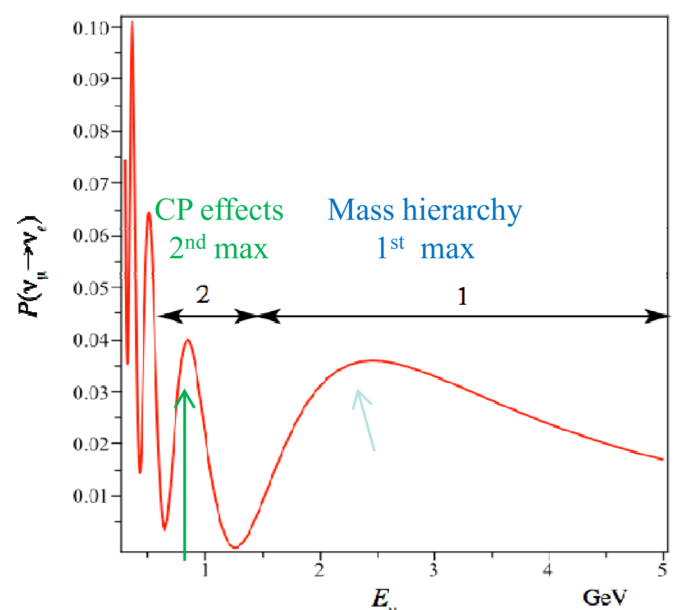


Main Injector

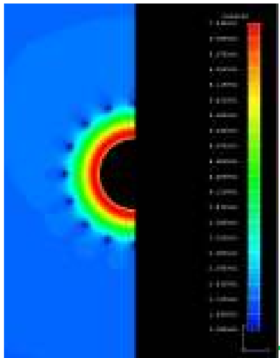
Design evolved from NuMI/MINOS and ANU/NOvA

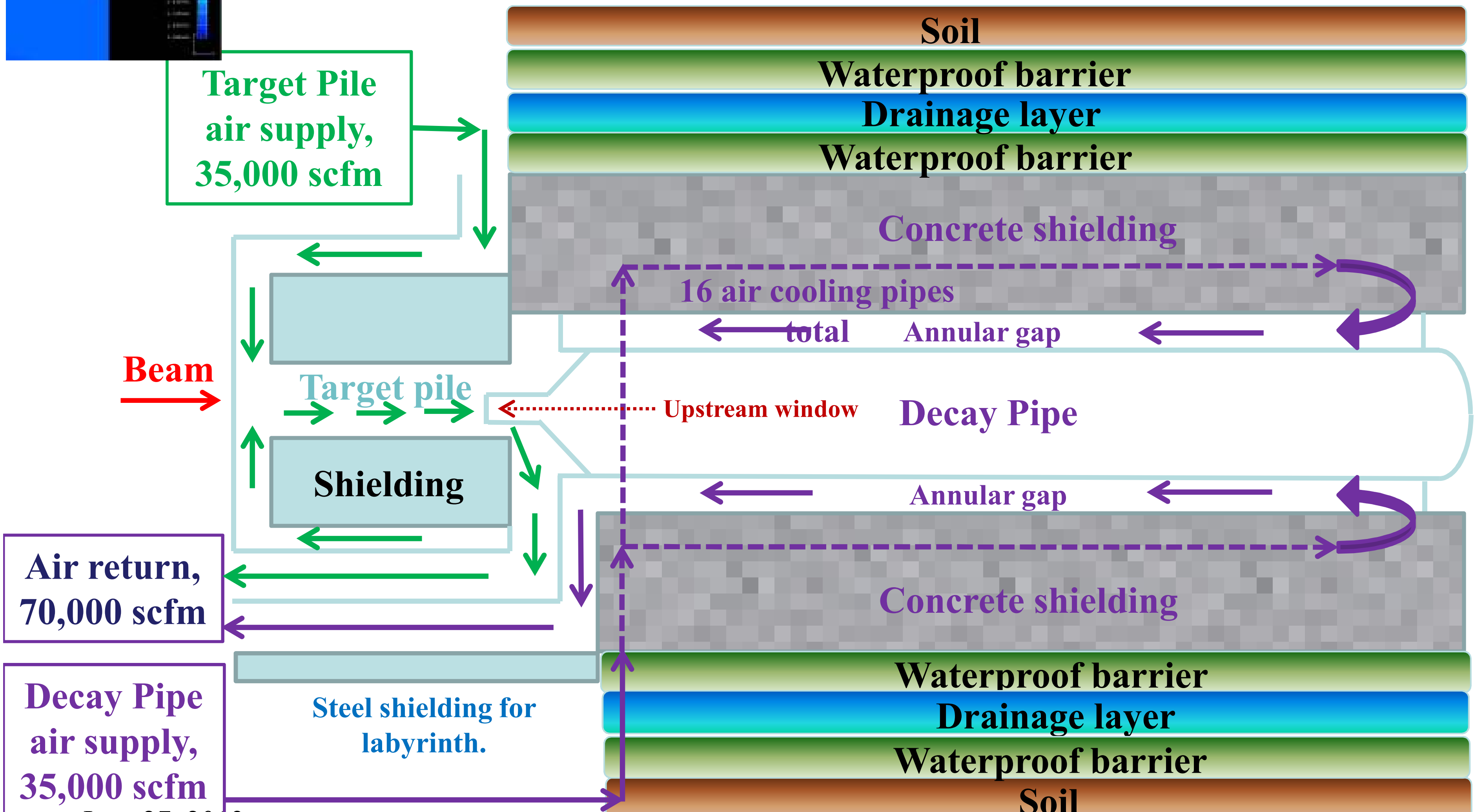
Beamline Requirements & Assumptions

- The driving physics considerations for the LBNE Beamline are the long baseline neutrino oscillation analyses.
- Wide band, sign selected beam to cover the 1st and 2nd oscillation maxima. Optimizing for E_ν in the range 0.5 – 5.0 GeV.
- The primary beam designed to transport high intensity protons in the energy range of 60-120 GeV to the LBNE target (focusing on 120 GeV).
- Start with a 708 kW beam (ANU/NOvA at 120 GeV), and then be prepared to take profit of the significantly increased beam power (~2.3 MW) available with Project X allowing for an upgradability of the facility.

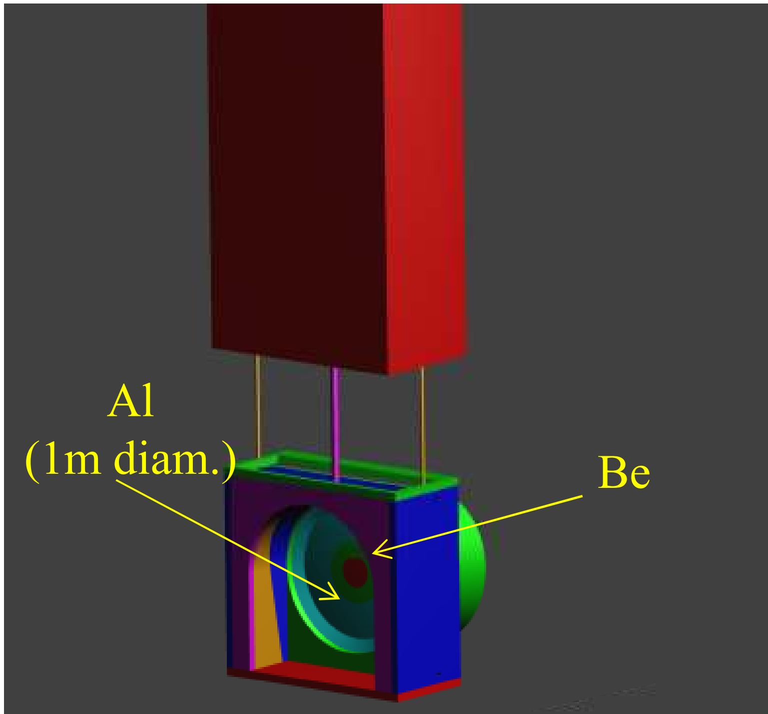


Helium-filled decay pipe, air-cooled.
Concentric decay pipe, both pipes are ½" thick.

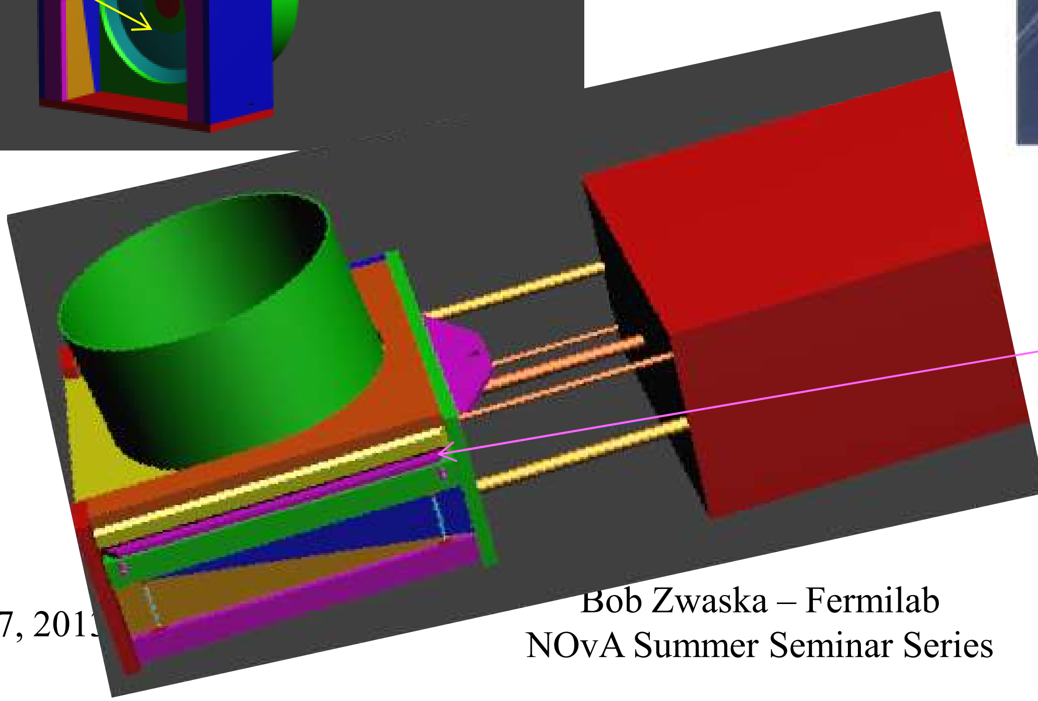


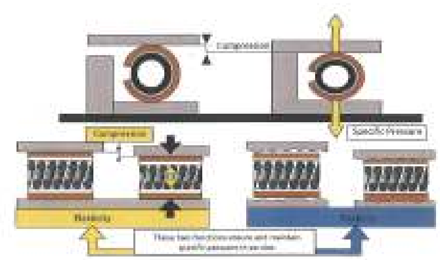


Replaceable Decay Pipe Window



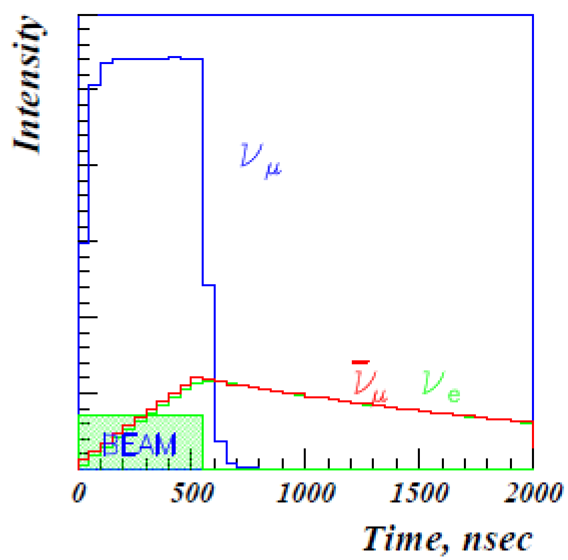
- Hybrid window consisting of aluminum and beryllium
- Helicoflex Seal
  - Uses compressible gasket between large surfaces and differential pumping
- Mounted on a remote handling fixture

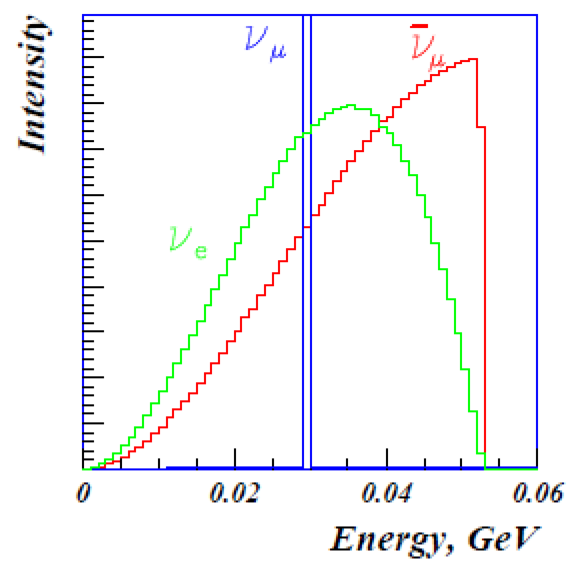




Decay at Rest "Beams"

- Create copious pions from a high-energy proton beam
  - Stop them all in a target
  - Most π^- absorbed into nuclei
  - π^+ decay – subsequent μ^+ also decay
- Produced "beam" is isotropic and consists of three flavors
  - Muon neutrinos are below the threshold for muon production
  - Primary search is the appearance of anti-electron-neutrinos through positron production
- Basis for LSND, and proposed for future experiments





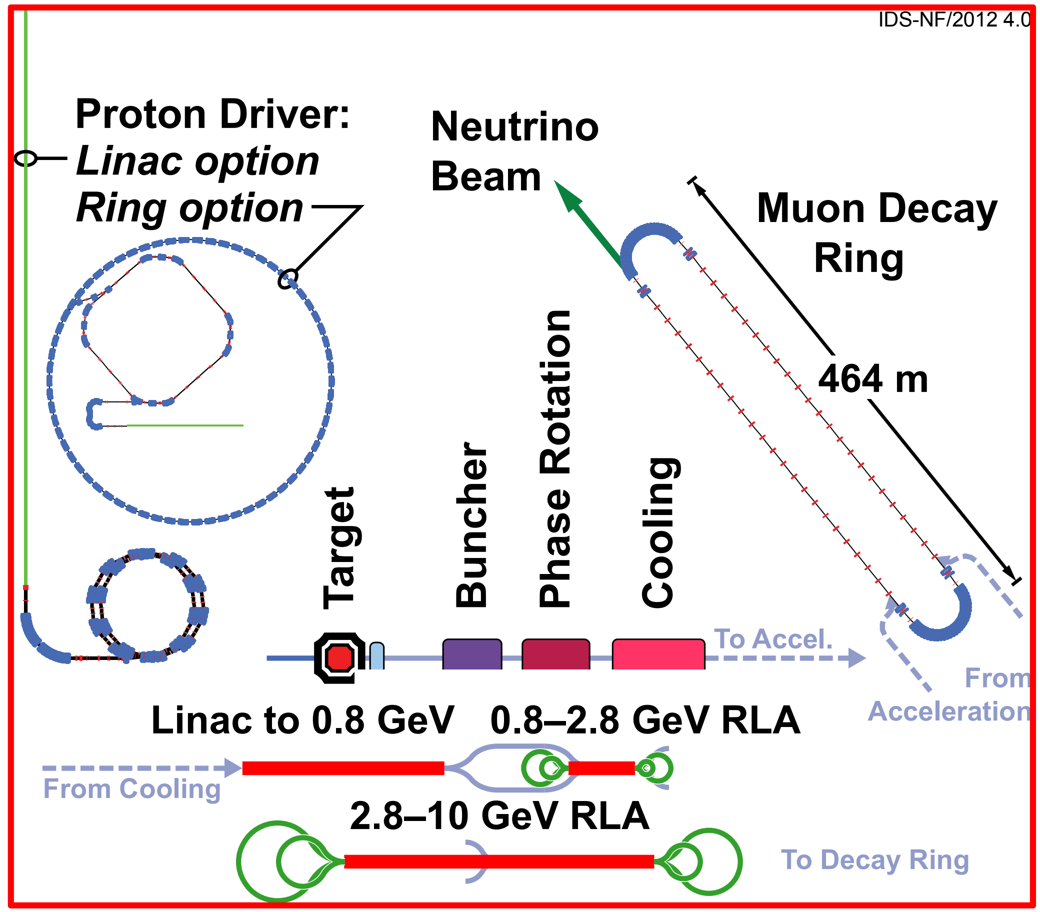
Neutrino Factories

- Produce muon beams to decay into neutrinos

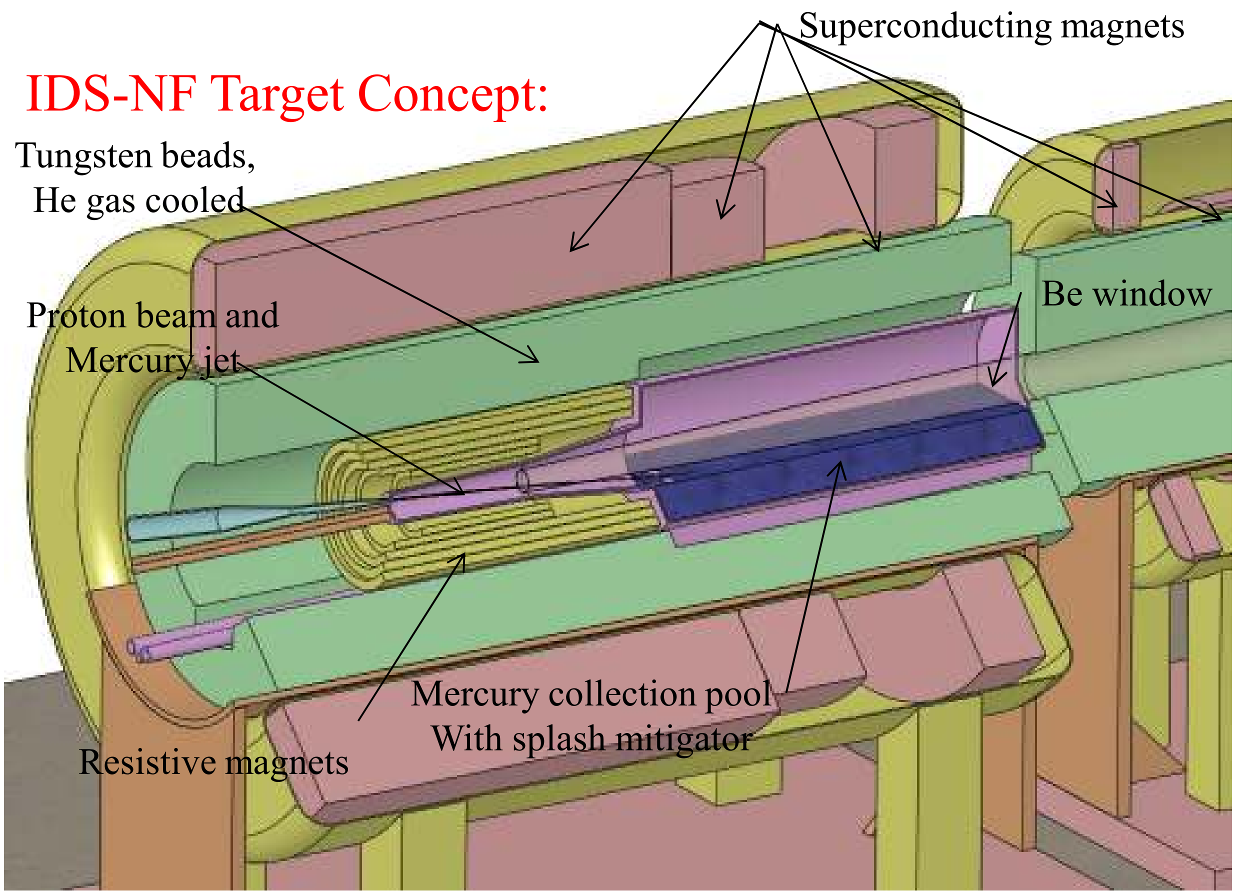
$$\mu^+ \rightarrow e^+ \overline{\nu}_\mu \nu_e$$

$$\mu^- \rightarrow e^- \nu_\mu \overline{\nu}_e$$

  - ➢ Primary search is muon-neutrino appearance
    - Requires detector to have excellent muon charge discriminations
- Many technical challenges
  - ➢ Multi-MW primary beam in very small bunches
  - ➢ Target / focusing system
  - ➢ Unique/enormous magnets
  - ➢ Cooling the muons to fit into a decay ring
  - ➢ Extremely rapid acceleration
  - ➢ Messy decay ring
- All the above makes this very interesting to look at



NF Target Station



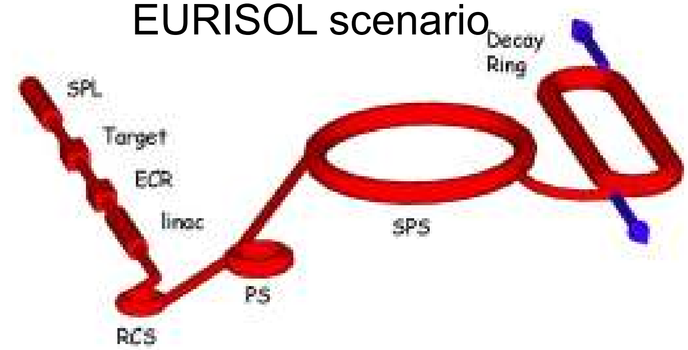
Shielding of the superconducting magnets from radiation is a major issue.

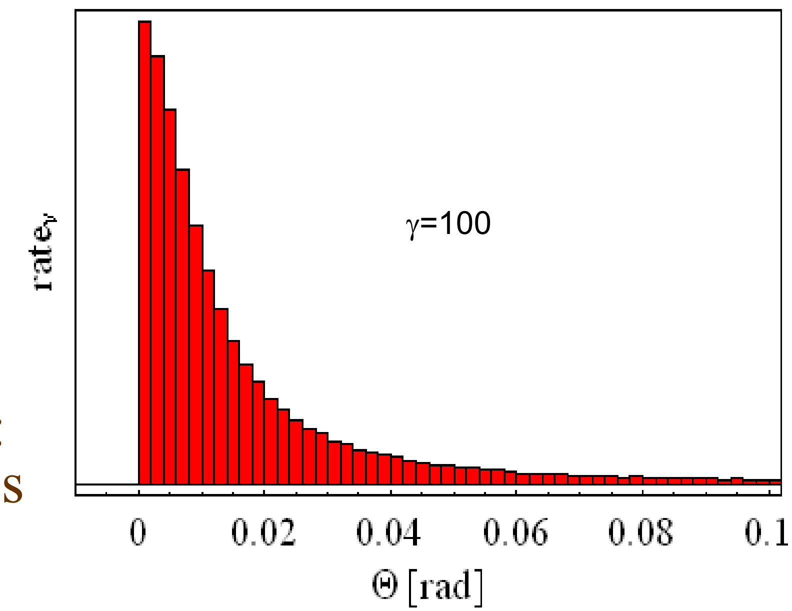
Magnet stored energy ~ 3 GJ!

Beta Beams

- Accelerate unstable nuclei to γ = 100-500
  - Typical lifetimes of minutes
  - Simplifies collections and acceleration
- Beta-decay electron- neutrinos of several MeV in rest frame
  - Boost brings it to useful energies
  - Search for muon-neutrino appearance
  - Small *Q* produces a more focused beam
- Beam is pure!
  - No muon contamination, except from showers of decay nuclei
- Ions of choice: ^{6}He and ^{18}Ne
- Not currently receiving much attention: making the ions in sufficient quantity is just too difficult

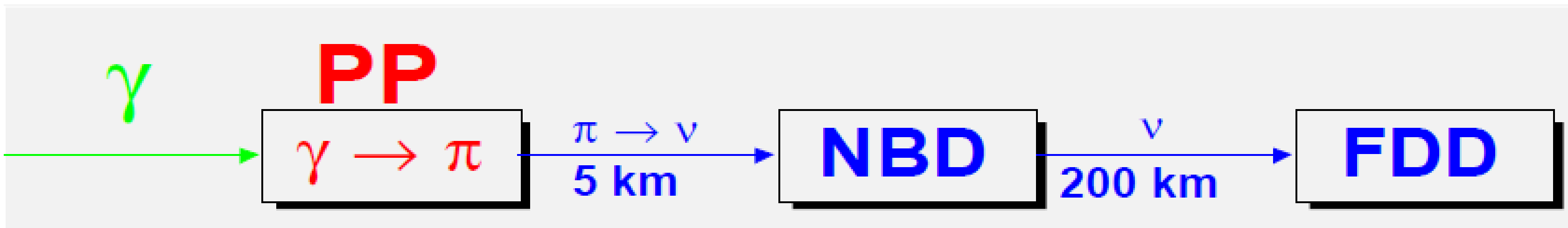
EURISOL scenario





Electron Produced Beams

- Use ILC-like waste beams
  - 10s of MW of electron/positron power
  - Convert leptons to brehmsstrahlung photons
- Photonuclear reactions to produce pions, Lambdas, etc.



Various proposals, figure from I. F. Ginzburg

- Not the most efficient way to produce a neutrino beam, but a good use of already-existing beam, if it exists

Conclusion

- Neutrino beams have been used for over 50 years
  - Oscillations are only the latest application

- Neutrino beams are now high-power and high-precision
  - Verging on MW beams
  - Precision demands continue to increase

- Numerous challenges to be addressed moving forward
  - Numerous potential innovations that can make an impact

How to Make a Neutrino Beam

Robert Zwaska

Fermilab

June 27, 2013

NOvA Summer Seminar Series